FOUNDATIONS OF FUTURE ELECTRONICS

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Preface

Electronics presents vivid examples of topics, formerly the domain of pure scientists, which in a short space of time have become of current technological importance. The aim of this book is to introduce the engineer and applied scientist to current thinking and advances in those selected areas believed most likely to have impact on electronics in the future. The book is neither exhaustive nor profound, but is intended to be interesting and useful in answering gross questions for the inquiring nonspecialist. The expositions are keyed to seriously interested graduates in science and engineering.

The first section deals with matter as individual atoms in paramagnetic and nuclear resonant phenomena, and as solid aggregates in ferromagnets, semiconductors, and superconductors. An introduction is presented under the broad heading of molecular engineering. Plasmas, the logic of which emphasizes statistics and continua rather than single particles and lattices, are included under a separate heading. The next section shows that electrons moving freely in vacuum, from the study of which electronics was born, seem certain to perform in ways productive of new results for the future. The final treatments deal with two features of the electronic environment which show promise of longevity, namely, the presence of noise and the requirement to transmit information and energy through a channel.

The title, chosen before details were worked out, traps authors as well as editors in the role of prophet. They lacked experience, and found that there are occupational hazards. For glaring omissions—e.g., the use of electronic techniques for rocket propulsion—the editors can only plead lack of space, foresight, or both. The perilous rate at which the future viewed from 1959 has become the past as of 1961 is already clear from examples. The achievement of coherent light by stimulated emission was predicted as a possibility for 1960 during the series of lectures, and references are included in this volume. But no speaker was optimistic enough to predict within 80 db the level and degree of success actually achieved. The new possibilities in the realm of high magnetic fields opened up by hard superconductors were not explicitly forecast. It is comforting that the foundations for both these developments are well laid in the appropriate chapters. The editors are grateful for the response shown by the authors to the aim and spirit of the course.

A number of previous University of California Extension courses intended to serve the scientific and industrial community have established the pattern followed in this volume, in which topflight authorities cover broad fields in separate presentations. The lectures collected in the present volume were presented in 1959–1960 under the auspices of University Extension in four locations in the State of California: Los Angeles, San Diego, Corona, and Palo Alto. Dean L. M. K. Boelter of the College of Engineering at UCLA deserves thanks for encouraging the series as a whole. Dr. Simon Ramo, Executive Vice President of Thompson Ramo Wooldridge Inc., and J. C. Dillon, Engineering Extension, furnished the initial impetus. Clifford Bell and Tod Singleton aided materially in ensuring the success of the lectures by the help they rendered, while Mrs. Virginia McGuckin served effectively as Secretary.

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Molecular Engineering

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When exploration opens a world of new dimensions, our old habitats suddenly look shopworn and unexciting, until balance is restored in a setting of wider horizons. This "being pushed off the center of the stage" happens at present to classical engineering. Its constructions, tests, and ideas derive from macroscopic concepts of daily experience; but behind this structure of familiar phenomena science discerns, with rapidly increasing clarity, the molecular world in action. Macroscopic properties become understandable expressions of molecular events; and as fast as the new insight of "molecular science" emerges, it can be applied as "molecular engineering" for designing materials and devices to order [*1*].*

New fields of learning normally breed new specialists, and the augmented confusion of tongues brings nearer the catastrophe of the Tower of Babel. The advent of "molecular science and molecular engineering," in contrast, acts as a decisive antidote: It obliterates the barriers separating departments and schools in a great drive for synthesis and application of knowledge in the realm of atomic dimensions. Into this setting fits the course "Foundations of Future Electronics" as a farsighted effort of the University of California to ally scientists and engineers by visions of new things to come. It is the obligation of the opening lecture to introduce concepts and procedures for this molecular chess play of the future.

1.1 From Classical to Quantum Concepts

In classical physics cause and effect rule unchallenged, and past and future can be calculated in principle by the laws of mechanics and electromagnetism if the positions, velocities, and charges of all particles are

* Numbers in brackets refer to the numbered list of references at the end of the chapter.

ascertained for a given instance. Classical statistics, with its probability statements, does not intend to shake this inherent confidence in certainty; it is the lazy man's approach of avoiding cumbersome individual accounting by means of averaging the behavior of many identical systems. In resolving the contradiction between classical statistics and the laws of thermal radiation, Planck discovered the *quantum of action* [2]

$$h = 6.625 \times 10^{-34} \text{ [joule-sec]} \tag{1.1}$$

Its existence destroyed the validity of the classical approach in the realm of atomic dimensions.

Einstein's conclusion [3] that any radiation process involves the emission or absorption of individual light quanta or *photons* of the energy and momentum

$$\begin{aligned} \mathcal{E} &= h\nu \\ p &= \frac{h}{\lambda} \end{aligned} \tag{1.2}$$

led to Bohr's model of the atom [4]. The spectra of atoms had been ordered empirically by the *Rydberg-Ritz combination principle* into series of lines represented as the difference of two terms

$$\nu = Rc\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \tag{1.3}$$

with R the Rydberg constant, c the light velocity, n_1 a fixed integer characterizing a series, and n_2 a running integer ranging from $n_1 + 1$ toward ∞. Rutherford had discovered the nucleus [5] of subatomic dimension, in which the mass of the atom, positively charged, is concentrated. Bohr visualized the structure of the compensating electron atmosphere as a discrete sequence of stabile planetary orbitals—a stability violating classical electrodynamics—and postulated that atomic systems change their energy content discontinuously by quantum transitions between stationary electronic states as

$$\mathcal{E} = h\nu = hRc\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) \tag{1.4}$$

By adding that in the limit of large dimensions, i.e., many quanta, the behavior of atomic systems asymptotically approaches that of classical systems (*correspondence principle*), Bohr could calculate quantitatively the Rydberg constant, the radii of the orbits, and the spectral lines resulting. The excitation of spectra by the inelastic impact of electrons on atoms in the *Franck-Hertz experiment* [6],

$$\text{Kinetic energy loss } \tfrac{1}{2}mv^2 = \text{photon energy } h\nu \tag{1.5}$$

confirmed by direct experiment that steplike transitions between energy states, ruled by the quantum of action, are a decisive feature of the molecular world.

Such quantum processes are incompatible with the deterministic description of classical physics. The concept "transition" implies that the initial and final states (i.e., past and future together) control the occurrence of an event; and the sequence of steady states allows frequently competing choices. Hence, a quantum event cannot be forecast with certainty but only expected with an inherent probability.

Here one might argue that weather forecasting is in a similar dilemma, and increasing knowledge of wind and cloud patterns, temperature distribution, etc., will eventually transform the gambling commentator into an honest man. However, the existence of the quantum of action eliminates the probability of ever describing atomistic events in the space-time framework with the accuracy expected by classical physics, because the act of observation causes quantized exchanges of energy or momentum between measuring instrument and object. This restriction was first formulated by *Heisenberg* in his *uncertainty relations* [7]

$$\begin{aligned} \Delta\mathcal{E}\,\Delta t &\simeq h \\ \Delta p\,\Delta q &\simeq h \end{aligned} \tag{1.6}$$

Equation (1.6) states that energy $\mathcal{E}$ and time t are conjugated variables, as are momentum p and position q, and that the conjugated parameters are interdependent in their latitude of observation because of the quantum of action. This dry statement of intrinsic uncertainty replaces the divine confidence of classical science (Fig. 1.1).

The ensuing formulation of quantum mechanics by a very abstract symbolism of matrices proved—fortunately for the experimentalist—amenable to a more graphical interpretation. De Broglie's intuition [8] that Einstein's dualistic description of photons as particles and waves [Eqs. (1.2)] might also apply to the particles of matter was confirmed by the *electron diffraction* experiment of Davisson and Germer [9] and quantitatively formulated in *Schrödinger's wave equation* [10].

Any wave phenomenon of amplitude ψ, spreading through space unattenuated with a periodicity λ, has to obey the differential equation

$$\nabla^2\psi + \left(\frac{2\pi}{\lambda}\right)^2 \psi = 0 \tag{1.7}$$

Replacing the wavelength λ with the momentum p according to de Broglie's supposition

$$p = \frac{h}{\lambda} \tag{1.8}$$

and recalling that the kinetic energy $\mathcal{E}_{\text{kin}}$, the difference of total energy $\mathcal{E}$

and potential energy U of a system, is correlated to the momentum as

$$\mathcal{E}_{\text{kin}} \equiv \mathcal{E} - U = \frac{p^2}{2m} \tag{1.9}$$

results in Schrödinger's wave equation for stationary states:

$$\nabla^2\psi + \frac{2m}{\hbar^2}(\mathcal{E} - U)\psi = 0 \tag{1.10}$$

where

$$\hbar \equiv \frac{h}{2\pi} \tag{1.11}$$

The local intensity $\psi\bar{\psi}\,dV$ of this wave, as Born first pointed out [11], describes the relative probability of finding the particle in the volume

Angel propelling planet

$$\Delta\mathcal{E}\,\Delta t \geq \hbar$$

$$\Delta p\,\Delta q \geq \hbar$$

Heisenberg uncertainty relations

Fig. 1.1 From classical certainty to quantum-mechanical probability. Angel propelling globe; anonymous engraving on a Tarocchi playing card, North Italy, fifteenth century. (*Reproduction by courtesy of Museum of Fine Arts, Boston.*)

element dV. Since the particle obviously is somewhere, the integral of the intensity of the *probability wave* extended over all space must be unity (i.e., contain it with certainty),

$$\oint_V \psi\bar{\psi}\,dV = 1 \tag{1.12}$$

$\bar{\psi}$ represents the complex conjugate of ψ.

De Broglie's correlation between momentum and wavelength [Eq. (1.8)] leads to a first understanding of the stability of Bohr's electron orbits. The circumferences of the circular orbits of the hydrogen atom turn out to be simply a sequence of standing waves (Fig. 1.2)

$$2\pi r_n = n\lambda \qquad n = 1, 2, 3, \ldots \tag{1.13}$$

It also dawns on us why the mass of an atom must be concentrated in a small nucleus. An electron rotating in the coulomb field of a proton, just like a satellite rotating in the gravitational field of the earth, is in mechanical balance only if its kinetic energy equals one-half of its potential energy (virial theorem); i.e.,

$$\frac{p^2}{2m} \equiv \frac{h^2}{2m\lambda^2} = \frac{e^2}{\epsilon_0 8\pi r_n} \tag{1.14}$$

The ground state of the hydrogen atom ($n = 1$) has, according to Eqs. (1.13) and (1.14), the radius

$$r_1 = \frac{\epsilon_0 h^2}{\pi m e^2} \simeq 0.528 \times 10^{-10}\,[\mathrm{m}] = 0.528\ \mathrm{A} \tag{1.15}$$

If a proton were similarly bound as a standing wave λ, the radius would have to contract by the ratio of the masses,

$$\left.\begin{aligned} m_+ &\simeq 1.6725 \times 10^{-27}\ \mathrm{kg} \\ m &\simeq 9.107 \times 10^{-31}\ \mathrm{kg} \end{aligned}\right\} \frac{m_+}{m} \simeq 1{,}836.5 \tag{1.16}$$

to about 2.8×10^{-14} [m] and the binding energy increase from tens to tens of thousands of electron volts. Actually, short-ranging nuclear forces take over, binding with millions of electron volts and shrinking the radius and with it the wavelength to the order of 10^{-15} m.

Figure 1.2 in its simplicity is instructive but misleading. Obviously Heisenberg's uncertainty relations [Eqs. (1.6)] and thus the spirit of quantum mechanics are violated by assigning simultaneously a fixed momentum and orbit to the electron. The energy of stationary states may be defined quite accurately since the time of observation (Δt) can be very long; but the assumption of an accurate wavelength ($\Delta p \to 0$) makes the position of the electron spread in a probability pattern over all space ($\Delta q \to \infty$). To find the shape of these standing-wave modes requires solving Schrödinger's equation [Eq. (1.10)].

At this juncture enters the main dilemma of quantum mechanics. The wave equations of the electromagnetic field can be solved in principle; they describe the statistics of noninteracting photons, and complications arise mainly from boundary conditions. The wave equation of quantum dynamics, in contrast, refers to the probability behavior of an individual particle (an electron, for example), which interacts with all other particles of the system. Consequently, we are in general faced with *multibody problems* not amenable to exact solution. Optically speaking, the wavelength is apt to change from point to point in space and time; hence, the

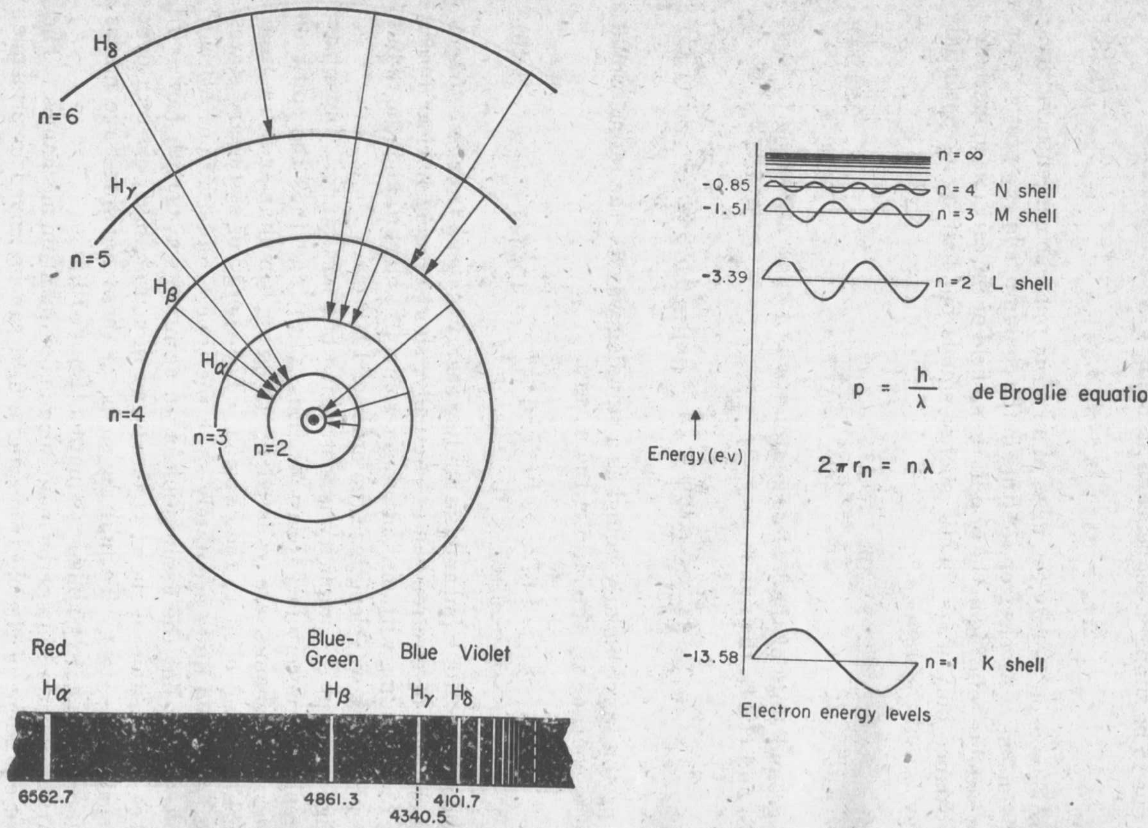

Fig. 1.2 Bohr's stationary orbits as standing-wave patterns.

wave modes have to be drawn through extremely dispersive, fluctuating media.

1.2 Atoms and Periodic System

The sequence of atoms arises by a systematic increase of the positive nuclear charge in steps of one elementary charge,

$$|e| \simeq 1.602 \times 10^{-19} \text{ [coulombs]} \tag{1.17}$$

with a simultaneous stepwise addition of one electron to the neutralizing negative atmosphere. Since the nuclear radii (ranging from about 1 to 9×10^{-15} [m]) are extremely small compared to those of the electron clouds (measured in angstrom units), the decisive binding force stems from the unspecific electrostatic field, and the nuclear structure affects only minute details of the electron atmosphere. Still, such *hyperfine structure* effects have already become of technical importance, as will be shown later.

The electronic structure of atoms can be treated fairly well as a one-center problem. Its prototype H, the two-body constellation of one electron rotating about a proton, can be solved accurately; by applying these solutions to multielectron systems in a similar approach (*hydrogen-like wave functions*), rough electron-cloud configurations can be calculated for all atoms by successive approximations [*12*].

The wave equation of the hydrogen atom, in agreement with Bohr's model [Eq. (1.4)], has solutions for the bound electron only when its total energy corresponds to one of the discrete *eigenvalues*

$$\mathcal{E}_n = \frac{Rhc}{n^2} \qquad n = 1, 2, 3, \ldots \tag{1.18}$$

The energy Rhc itself represents the greatest trap depth or, vice versa, the *ionization energy* of the hydrogen atom

$$Rhc \equiv 1 \text{ [rydberg]} \simeq 13.53 \text{ [ev]} \simeq 312 \text{ [kcal/g mole]} \tag{1.19}$$

The *rydberg* and the *electron volt,*

$$1 \text{ [ev]} \simeq 1.602 \times 10^{-19} \text{ [joule]} \tag{1.20}$$

the energy acquired by an electron in free fall through a potential difference of 1 volt [cf. Eq. (1.17)], are convenient yardsticks of binding energies in the molecular world. The *principal quantum number n*, by designating an average distance from the nucleus, divides the electron atmosphere of atoms into a sequence of shells [cf. Fig. 1.2 and Eq. (1.13)]. While the standing-wave modes of the electrons obviously extend through space, their intensity maxima are correlated to this *shell structure of the atoms.*

The wave equation for the ground state ($n = 1$) of the hydrogen atom

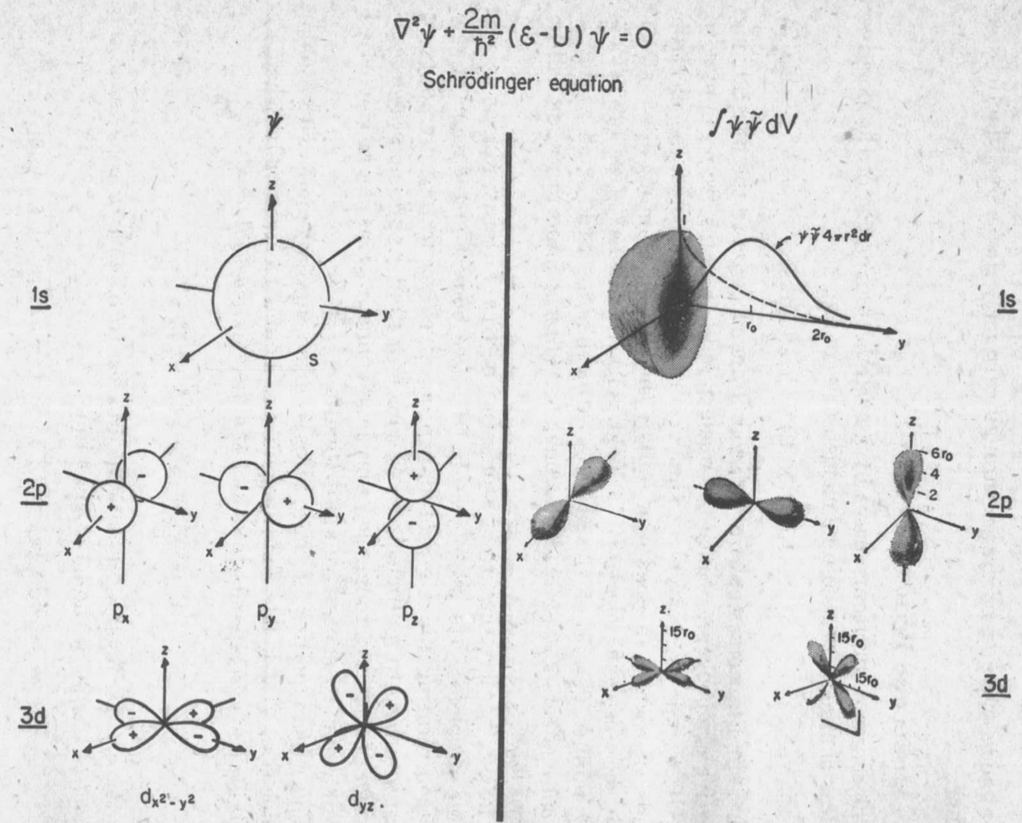

Fig. 1.3 Probability wave functions of hydrogen atom states.

has only one solution, a spherical symmetrical or *s function;* for the excited states ($n > 1$), in addition to one s function each, $(n - 1)$ eccentric wave-mode types are also solutions (Fig. 1.3). This situation is analogous to Bohr's original model where, in addition to a spherical orbit, $(n - 1)$ elliptical orbits of equal energy were admitted. However, at this point a significant difference in interpretation enters.

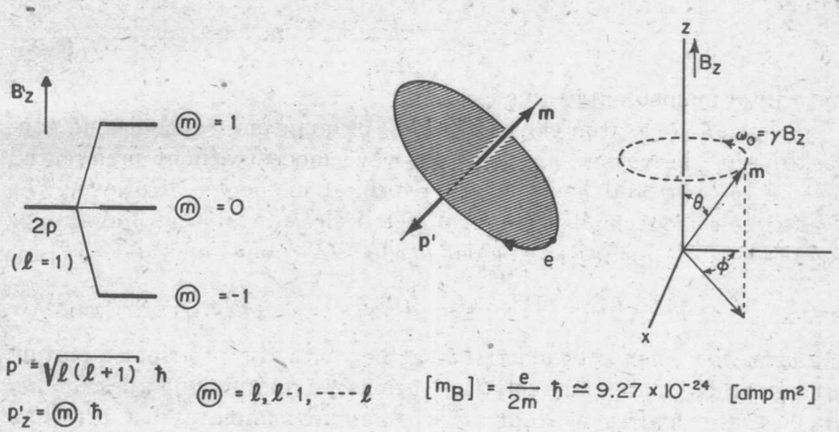

Fig. 1.4 The orbital electron as a gyroscope.

Classical physics describes an electron, circling a proton ν times per second in an orbit of radius r, as a *gyroscope* (Fig. 1.4) of the *mechanical angular momentum*

$$\mathbf{p}' = mv r\mathbf{n} = m(\nu 2r\pi)r\mathbf{n} \tag{1.21}$$

and a correlated *orbital magnetic moment* (current times surrounded area)

$$\mathbf{m} = -e\nu r^2\pi\mathbf{n} = -\frac{e}{2m}p' \tag{1.22}$$

where $\mathbf{n}$ represents a unit vector normal to the plane of the orbit. Bohr's model adds that only those circular orbits are stabile that fit the quantized angular momenta [cf. Eqs. (1.8), (1.11), and (1.13)]

$$p' \equiv pr_n = \frac{h}{\lambda}r_n = n\hbar \tag{1.23}$$

(*quantization condition of th rotator*). The magnetic moments $\mathbf{m}$ therefore become multiples of an elementary magnetic moment, the *Bohr magneton*

$$|\mathbf{m}_B| = \frac{e}{2m}\hbar \simeq 9.27 \times 10^{-24} \text{ [amp-m}^2\text{]} \tag{1.24}$$

The ratio of magnetic moment to angular momentum; the *gyromagnetic ratio*

$$\gamma \equiv \frac{|\mathbf{m}|}{|\mathbf{p}'|} = \frac{e}{2m} \tag{1.25}$$

has still the classical value. Normalized in terms of the Bohr magneton and of $\hbar$, this ratio is known as the *g factor* (or spectroscopic splitting factor)

$$g \equiv \gamma \frac{\hbar}{\mathbf{m}_B} \tag{1.26}$$

For orbital moments its value is 1.

The spherical electron clouds (*s states*) of quantum mechanics, in contrast to this derivation, are standing-wave modes without preferential electron motion, and hence have no orbital moments. However, the eccentric electron clouds contain directed electron motion and can be characterized by quantized angular mechanical momenta

$$p' = l(l+1)\hbar \qquad l = 0, 1, 2, \ldots, n-1 \tag{1.27}$$

The *azimuthal quantum number* l, together with the principal quantum number n, designates uniquely the various wave-function types (*orbital types*) of the hydrogen atom. The rules are simple: To a principal quantum number n belong n types; one of them is spherical (*s function*), and hence without angular momentum ($l = 0$); the others, ranging in angular momentum number from $l = 1$ to $l = (n - 1)$, are named for historical reasons *p function* ($l = 1$), *d function* ($l = 2$), *f function* ($l = 3$), and then alphabetically g, h, . . . , etc.

Each orbital type, in addition, comprises $(2l + 1)$ individual orbitals that can be distinguished in their orientation to a physical space-coordinate system (x,y,z). Without actual space orientation, the orbital types and orbitals for the same principal quantum number n are *degenerate*, i.e., correspond to the same energy. Table 1.1 summarizes the multiplicity of standing-wave modes for the hydrogen atom.

One physical reference axis can be provided conveniently by applying a uniform magnetic field. Such a field produces a torque $\mathbf{T}$ on the quantum-mechanical gyroscope proportional to the sine of the inclination angle by coupling to the orbital magnetic moment $\mathbf{m}$,

$$\mathbf{T} = \frac{d\mathbf{p}'}{dt} \equiv \mathbf{m} \times \mathbf{B} = \mathbf{m} \times \mu_0\mathbf{H} \tag{1.28}$$

Since the angular momentum $\mathbf{p}'$ and the magnetic moment $\mathbf{m}$ are correlated through the gyromagnetic ratio [cf. Eq. (1.25)], Eq. (1.28) can be rewritten

$$\frac{d\mathbf{m}}{dt} = \gamma(\mathbf{m} \times \mu_0\mathbf{H}) \tag{1.29}$$

and, for a static magnetic field $\mathbf{H} = H_z$, resolved into the component equations

$$\frac{d^2m_x}{dt^2} = -\gamma^2\mu_0{}^2H_z{}^2m_x$$
$$\frac{d^2m_y}{dt^2} = -\gamma^2\mu_0{}^2H_z{}^2m_y \qquad (1.30)$$
$$\frac{dm_z}{dt} = 0$$

The oscillatory x and y components are out of phase by 90° in space and

Table 1.1 Standing-wave Modes of the Hydrogen Atom

Shell	Quantum number			Orbital	
	Principal n	Azimuthal $(0 \rightarrow n - 1)$ l	Magnetic $(l, l - 1, \ldots, -1)$	Type (n,l)	Number $(2l + 1)$
K	1	0	0	s	1
L	2	0 1	0 1, 0, −1	s p	1 3
M	3	0 1 2	0 1, 0, −1 2, 1, 0, −1, −2	s p d	1 3 5
N	4	0 1 2 3	0 1, 0, −1 2, 1, 0, −1, −2 3, 2, 1, 0, −1, −2, −3	s p d f	1 3 5 7
O	5	0 1 2 3 4	0 1, 0, −1 2, 1, 0, −1, −2 3, 2, 1, 0, −1, −2, −3 4, 3, 2, 1, 0, −1, −2, −3, −4	s p d f g	1 3 5 7 9

time, and hence add up to a circular rotation in the xy plane, i.e., a *precession* of the gyroscope around the field axis with a resonance or *Larmor frequency* (cf. Fig. 1.4)

$$\omega_0 = \gamma\mu_0H_z \qquad (1.31)$$

μ_0 is the permeability of free space [*13*]

$$\mu_0 = 4\pi \times 10^{-7} \text{ [henry/m]} \qquad (1.32)$$

For the classical gyromagnetic ratio [cf. Eqs. (1.25) and (1.26)],

$$\gamma = \frac{e}{2m} \frac{|\mathbf{m}_B|}{\hbar} \simeq 8.74 \times 10^{10} \text{ [coulomb/kg]} \qquad (1.33)$$